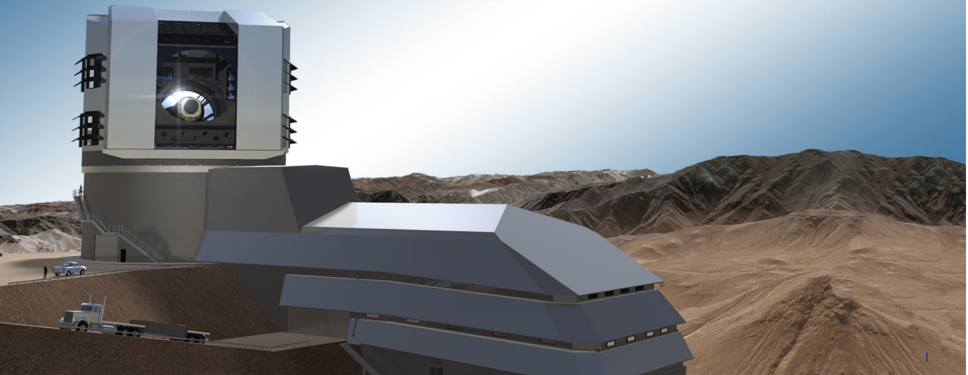
Flatfielding a Widefield Camera

Robert Lupton, Mario Jurić, and Christopher Stubbs

2014-12-04



Introduction and Notation

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We need to find

$$C_{std,b} \equiv \int_0^\infty F_\nu S_{std,b}\, d\lambda/\lambda$$

given $C_{raw,b}$ (where $S_{std,b}$ is some average $S^{atm} S_b^{sys}$).

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- -- Estimate the background level and $C_{raw,b}$

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-- Atmospheric Stuff (a 1.2m telescope with R $\sim$ 300 --- 400 spectrophotometry; two units to measure water vapour; a commercial all-sky monitor using GPS satellites and a bore-sight mounted radiometer to measure the profile)

The instrumental sensitivity $S_b^{sys}(\lambda, \boldsymbol{x})$

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Unfortunately, $\mathcal{F}_b$ also includes scattered light and ghosting:

$$\mathcal{F}_b(\lambda, \boldsymbol{i}) \equiv I(\lambda)\,(1 + i(\lambda, \boldsymbol{i}) + \mathcal{A}_b(\lambda, \boldsymbol{i}))\, \mathcal{S}_b(\lambda, \boldsymbol{i})$$

where $\mathcal{I} \equiv \mathcal{I}_0 + i(\lambda, \boldsymbol{i})$ is the result of non-illumination of the screen, and $\mathcal{A}_b(\lambda, \boldsymbol{i})$ is the effect of scattered light.

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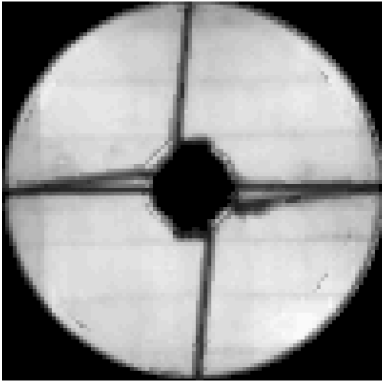
N.b. We wrote $\mathcal{S}_b$ not S_b^{sys} because there are multiplicative effects other than quantum efficiency that enter into $\mathcal{F}_b$ (*e.g.* pixel size variations).

$i(\lambda, \boldsymbol{i})$ and vignetting in HSC



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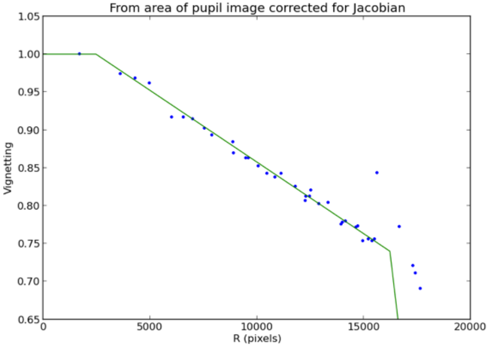

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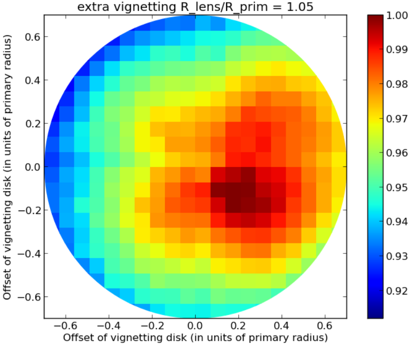

Multiplicative Effects

Structures seen in $\mathcal{S}_b$ can come from either QE variations in the system and vignetting, or changes in the effective size of the pixels:

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For measures of surface brightness QE/vignetting and geometrical effects are equivalent, but for measurements of objects' fluxes we must be careful to separate them; treating larger pixels as more sensitive can give incorrect results.

Star Flats

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We plan to use star flats as a cross-check, not a primary measurement.

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The projector will also generate a series of ghosts, but only a small portion of the pupil is illuminated.

Using the Collimated Projector

We need to allow for only illuminating a portion of the pupil. If we label the spots by ℓ, a single spot's flux is

$$P_b^\ell(\lambda, \boldsymbol{x}_i, \boldsymbol{X}) = a^\ell I(\lambda)\,(1 + i(\lambda))\mathcal{S}_b^{filt}(\lambda)\mathcal{S}^{tel,qe,vig,optics,ccd}(\lambda)$$

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If we now move these spots around the LSST focal plane, taking data at only a single position in the pupil and wavelength, we may solve for the spots' relative amplitudes.

Using the Collimated Projector

Once we know the a^ℓ's, we scale all the spot intensities to a common scale,

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and

$$\mathcal{F}_b(\lambda, \boldsymbol{x}_i) = P_b^\ell(\boldsymbol{x}_i) + I\,\mathcal{S}^{qe,optics,ccd} \int_{pupil} \mathcal{A}_b\mathcal{S}_b^{filt}\mathcal{S}^{tel,vig}\,d\boldsymbol{X}$$

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For many cameras the spatial structure of $\mathcal{A}$ has sharp features. Furthermore, the operations described above are expensive, and we have to repeat for every 1nm step in wavelength. If we know the filter bandpasses $\mathcal{S}_b^{filt}(\boldsymbol{i})$ at every point in the focal plane we may use a slightly different approach.

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By interpolating and then summing over the focal plane we have an estimate of $\mathcal{A}_b$; it will be interesting to see how well this works.

Flatfields

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Before we can create a flatfield image for band *b* we need to:

-- Decide what to do about $\mathcal{A}_b(\lambda, \boldsymbol{i})$

-- Decide what to do about $\mathcal{S}^{optics}(\lambda, \boldsymbol{i})$

-- Decide what to do about $\mathcal{S}^{ccd}(\lambda, \boldsymbol{i})$

-- Choose an SED

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$$(1 + \mathcal{A}_b)\mathcal{S}_b^{filt}\mathcal{S}^{tel}\mathcal{S}^{qe}\mathcal{S}^{optics}\mathcal{S}^{ccd}$$

Before we can create a flatfield image for band *b* we need to:

-- Decide what to do about $\mathcal{A}_b(\lambda, \boldsymbol{i})$

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-- it does not remove the need for sufficiently scrupulous algorithms to require access to the per-pixel geometrical information.

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This is the flatfield that best flattens the sky once warped onto a tangent plane, at the cost of photometric errors.

The object's SED

Let us remember that we don't actually need to know the SED; we need merely to know enough about it to allow us to make sufficiently accurate corrections from $C_{raw,b}$ to $C_{std,b}$.

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We don't know our objects' SEDs, but we do know their multi-band fluxes $\{C_b\}$ and other parameters θ (*e.g.* morphological information). There is a probability distribution $p(SED|\{C_b\}, \theta)$ which may be compact, essentially reducing to a single reasonably well-defined SED, or may reflect the intrinsic range of SEDs of objects with those properties.

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There is nothing we can do about this degeneracy, which means that we cannot hope to correctly estimate C_b^{std} for a subset of objects which we detect. We shall define a deterministic mapping from colour to SED$(\{C_b\}, \theta)$ which will allow a consumer of the data to make their own correction.

Measuring the background level

We plan to background match exposures before sky subtraction, generating a stacked image in a sky projection. This results in two data products:

- -- The background image in the stacked image B^{stack}.
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Because we measure B^{stack} in sky coordinates the geometrical distortion terms $\mathcal{S}^{optics}$ in the flat field illumination are automatically removed, and when we warp B^{i} back to the corresponding calibrated raw frame and subtract it we arrive at an image with $\mathcal{S}^{optics}$ fully accounted for.

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If we had included $\mathcal{S}^{ccd}$ in the flatfield we would have handled the background correctly if we also included it in the warps to and from sky coordinates, but we would not be able to forget about it as it continues to have effects on the astrometry and photometry.

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-- We could decide to now correct for $\mathcal{S}^{ccd}$.

Measuring C_b^{std}

The signal that we measure after (incorrectly) flat fielding with a flat constructed using the sky's SED is

$$I_j = a \int_b S_{obj}^{atm} \frac{\mathcal{S}_{b,j,obj}^{filt} \mathcal{S}_{j,obj}^{tel} \mathcal{S}_{j,obj}^{qe}}{\mathcal{S}_{b,j,sky}^{filt} \mathcal{S}_{j,sky}^{tel} \mathcal{S}_{j,sky}^{qe}} \mathcal{S}_j^{ccd} M_j P_b(\lambda)\, d\lambda + \epsilon_j \equiv a w_j + \epsilon_j$$

where I_j is the intensity of the j^{th} pixel and ϵ_j the noise.

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a =& \frac{1}{S^{atm}_{obj}} \frac{\mathcal{S}^{filt}_{b,sky}\mathcal{S}^{qe}_{sky}}{\mathcal{S}^{filt}_{b,obj}\mathcal{S}^{qe}_{obj}} \frac{\sum_j (\mathcal{S}^{ccd}_j M_j) I_j}{\sum_j (\mathcal{S}^{ccd}_j M_j)^2} \\
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and, correcting to a standard atmosphere, and writing $w = \mathcal{S}^{ccd}_j M_j$

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\equiv& \frac{S^{atm}_{obj,std}}{S^{atm}_{obj}} \frac{\mathcal{S}^{filt}_{b,sky}\mathcal{S}^{qe}_{sky}}{\mathcal{S}^{filt}_{b,obj}\mathcal{S}^{qe}_{obj}} C_{raw} \\
\equiv& c_{\mathrm{SED}} C_{raw}
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If we have *n* exposures this generalises to

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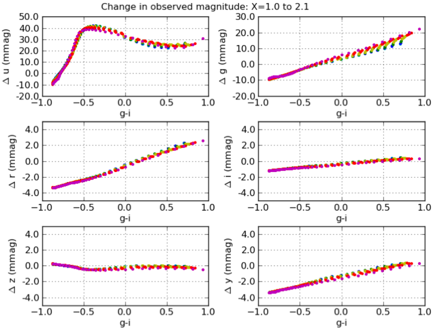
This relies depends on our assumption about the constancy of $\mathcal{S}^{tel}_{obj}/\mathcal{S}^{tel}_{sky}$ and $\mathcal{S}^{qe}_{obj}/\mathcal{S}^{qe}_{sky}$ over the object.

Colour Gradients

Because we using a model-based approach to handle SED dependencies we can easily handle more complicated problems; for example, if we are using a bulge/disk decomposition we are estimating the colours of each component, and can handle their SEDs separately when fitting our model.

The End

Stellar Photometry



The change in observed magnitudes due to changes in airmass from $X = 1.0$ to $X = 2.1$, for a typical atmospheric transmission response curve.

Using Sets of Stars

We will have many-colour photometry (*ugrizy*) of many, many stars in each visit. We know from simulations of Kurucz models that as the properties of the atmosphere are varied there are several percent level changes in fluxes, with percent-level scatter at a given $g - i$ colour. It is not yet clear how much of this scatter can be regressed out using all five available colours.

Even if the scatter can be removed to SRD precision it is not clear how well we will be able to characterize S^{atm} across the filter b.

Spatial Structure of the Atmosphere

Even if the photometry is unable to constrain S^{atm} well enough to satisfy the SRD requirements, it seems very likely that we will be able to say something interesting. Once we have implemented an initial version of the photometric analysis we will be able to analyse wide-field camera data to explore the structure functions.